7. CONSTRUCTION CONSIDERATIONS

This section of the report describes constructability considerations for large and small diameter rock tunnels, soft ground tunnels, and drop shafts in soil and rock. This includes excavation methods, support systems, and lining alternatives for the Fall Creek/White River Tunnel project.

7.1 SAFETY

Underground construction is subject to more safety related risks than most types of construction projects. These risks need to be managed during the design and construction of the project. During design, the safety related risks unique to the project should be defined and minimized, as described in Section 9 – Risk Management. The contract documents should require the tunneling contractor to be solely and completely responsible for safety conditions at the jobsite, including safety of all persons (including employees) and property during construction. Project safety provisions should conform to U.S. Department of Labor Occupational Safety and Health Administration (OSHA) requirements, specifically including, but not limited to, the Federal Occupational Safety and Health Act of 1970, as amended, and the Indiana Occupational Safety and Health Act. The Contractor should comply with the common law standards of due care and develop a Construction Safety Program that addresses all safety related concerns, which may require the need for a project safety officer. The Contractor should also comply with the U.S. Army Corps of Engineers safety requirements in Engineers Manual EM 385-1-1, if the project is managed by the Corps.

7.2 MAIN TUNNEL CONSTRUCTION

Depending on the required percent (95 or 97) capture and the selected alignment, the main tunnel's finished diameter and length will range from 26 to 35 feet and 7.5 to 10.5 miles, respectively. It is anticipated that the tunnel will be located in limestone and dolomitic rock at depths greater than 200 feet below ground surface (bgs).

7. CONSTRUCTION CONSIDERATIONS

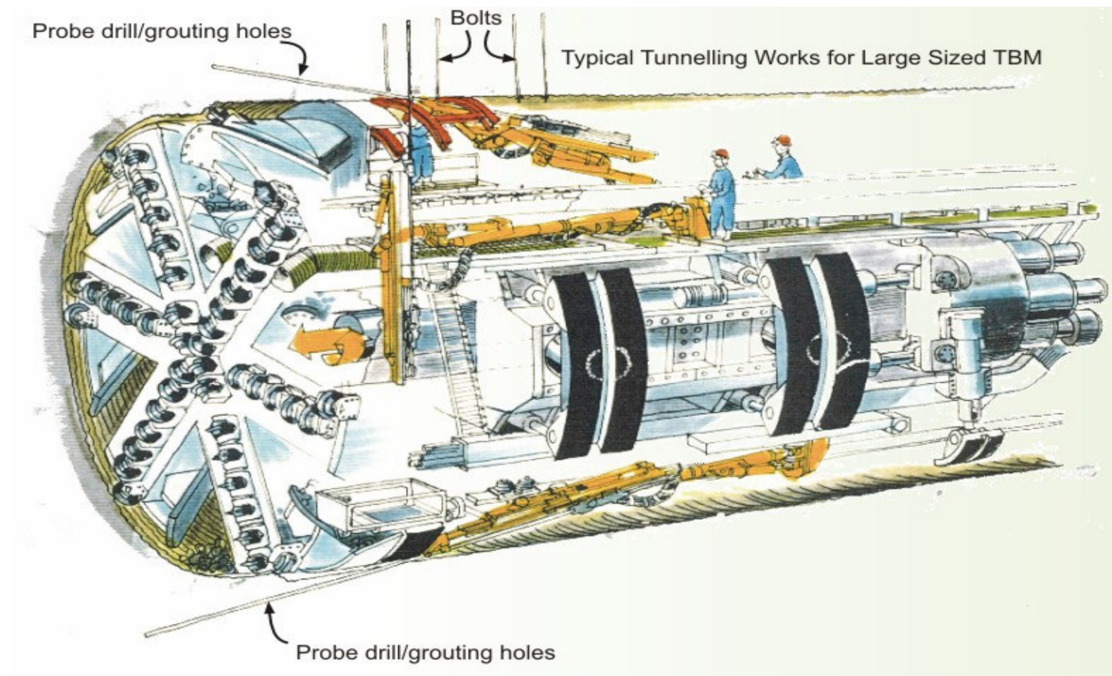
7.2.1 Excavation, Support and Lining

The Fall Creek/White River Tunnel can be excavated by drill-and-blast mining or mechanical excavation, such as a conventional tunnel boring machine (TBM) or an earth pressure balance machine (EPBM). The most economical mining method will be mechanical excavation using a TBM. Some advantages of mechanical excavation over drill-and-blast mining include:

- Potentially high average advance rates in favorable rock conditions from a single heading
- Excavation of a circular tunnel cross-section with minimal over-breaking of the rock that will require less concrete for lining
- Minimal impact on adjacent structures in terms of settlement of soils or blast vibrations
- Reduced initial rock support requirements
- Less labor intensive
- Provides a safer working environment
- Allows 24-hour work days in urban areas with minimal noise restrictions

Mechanical excavation, in particular a conventional TBM, can be used to mine through the carbonate rock anticipated for the Fall Creek/White River Tunnel project. A TBM mines the rock using a rotating circular cutterhead. The cutterhead rotates at a low revolution per minute. The rolling disc cutters on the face of the TBM cut the rock into chips, which are removed by a conveyor belt. Grippers push out against the rock and advance the TBM forward during mining. After a few feet of mining, the body of the TBM is pulled up to the cutterhead and re-gripped to the previously excavated wall and mining is resumed. Initial support is erected in the tail shield of the TBM. It is anticipated that the crown of the tunnel will require pattern rock bolts for initial support. In areas needing additional support, rock bolts should be supplemented with wire mesh, steel

7. CONSTRUCTION CONSIDERATIONS



Conventional TBM Equipped for Pre-Excavation Grouting

straps, channels, and circumferential steel sets with lagging. It is anticipated that the tunnel will be lined with unreinforced concrete along most of the alignment.

The concrete should be reinforced with steel, as required, to support zones of weaker rock and shaft connections. Typically, the cast-in-place concrete lining is installed following the mining of the entire tunnel. However, if hydrogeologic conditions indicate that groundwater inflows may significantly impact adjacent water wells, the concrete may be placed behind the TBM trailing gear while the tunnel is being mined. This installation method would significantly slow the advance rate of the tunnel, but would reduce the tunnel's impact on the existing water well fields.

7. CONSTRUCTION CONSIDERATIONS

Concrete Lining Operations

Following the placement of the concrete lining, the crown of the tunnel will require contact grouting to fill any voids in the concrete. In addition, to further minimize groundwater infiltration into the tunnel and exfiltration of combined sewer overflows (CSOs), cut-off grouting will be completed in the rock adjacent to the tunnel. Cut-off grouting is completed from within the tunnel by drilling short holes on a radial pattern into the rock to reduce the permeability. Cut-off grouting is conducted and continued until the allowable limit of groundwater infiltration into the tunnel is achieved. This limit of infiltration is established during design.

A slurry-face EPBM is a significantly more expensive alternative to the conventional TBM for mining rock. This closed-face tunneling method hydraulically prevents the infiltration of groundwater at the tunnel face by applying pressurized slurry consisting of water, bentonite and/or polymer conditioners. The full-face cutterhead is fully enclosed in a chamber filled with pressurized slurry to balance the existing ground and hydrostatic pressure. During mining, the cuttings are ground into small pieces and suspended in the slurry. The slurry is circulated out of the chamber to the surface through a pipeline. Slurry booster pumps typically are installed directly behind the cutterhead and at certain intervals in the tunnel. At the surface, the cuttings are separated and the slurry is treated and returned to the cutterhead chamber through a separate line. With an EPBM, water-tight gasketed pre-cast segmental concrete liners are used to line the tunnel. The segments are assembled and installed in the tail shield, and the annular space between the segments and rock is grouted.

Ground conditions will determine the most effective technique and equipment for mechanical excavation (conventional TBM or slurry-face EPBM). This determination can not be made until an exploration program has been conducted to obtain the geotechnical and hydrogeologic properties of the rock formations along the tunnel alignment. It is anticipated that dewatering along the main tunnel alignment will not be feasible because the tunnel is located 200 to 250 feet below the groundwater surface in a productive aquifer. Therefore, a groundwater control method other than dewatering will be required during excavation and lining. Groundwater control options include modifying the ground before excavation by pre-excavation grouting or tunneling with a water tight system such as slurry-face EPBM with gasketed concrete liner segments. Although the geologic and hydrogeologic properties of the rock require further definition, it is anticipated that pre-excavation grouting will be the most successful and cost effective technique to control groundwater. Pre-excavation grouting from the tunnel face helps to control and prevent high water inflows into the tunnel when mining.

Pre-excavation grouting entails advancing probe holes up to a couple hundred feet in front of the tunnel face and measuring the groundwater flow rate. If the groundwater flow rate into the probe holes exceeds a certain threshold value, primary grout holes are drilled and pressure-grouted along with the probe holes. Verification probe holes are then advanced to determine if additional grouting before advancing the TBM is necessary based on the inflow threshold value established for the project. Inflow threshold values would be determined upon conclusion of the geotechnical exploration program during the detailed design phase of the project. Once the rock is grouted sufficiently and allowed to setup for a minimum time period, the mining activities are resumed. Grouting consultants may be required depending on the rock and groundwater conditions discovered during further geotechnical investigations, and during construction.

7. CONSTRUCTION CONSIDERATIONS

Tunneling in rock using a slurry-face EPBM typically is more costly than using a TBM. EPBM advance rates are significantly less, which adds cost. The gasketed pre-cast segmental liners also can be at least twice as expensive as a cast-in-place concrete liner. In addition, successful mining of large diameter tunnels (30-foot diameter or greater) in rock under high hydrostatic pressures with a slurry-face EPBM has not been done in the United States. Therefore, until additional geotechnical and hydrogeologic information is available, it is anticipated that conventional mining using a TBM and a properly designed pre-excavation grouting program will be the more cost effective construction method.

7.3 CONNECTION TUNNEL CONSTRUCTION

Tunnels conveying CSOs from the drop shafts to the main tunnel will be constructed in rock and possibly soil depending on the selected main tunnel alignment. Approximately 20 connection tunnels will be required for this project.

7.3.1 Excavation, Support and Lining of Rock Connection Tunnels (Adits)

It is anticipated that relatively short connection tunnel lengths will be constructed in rock by drill-and-blast mining. Depending on the geotechnical and hydrogeologic properties, pre-excavation grouting of the rock from the tunnel face may be required prior to blasting to control groundwater inflow. Probing in front of the blast face and measuring the inflow rate will be performed to determine the need for pre-excavation grouting. If the measured flow rates exceed established design criteria, pre-excavation grouting will be performed in advance of the blasting face. Dewatering is not expected to be a viable option to control groundwater while constructing connection tunnels in rock.

Following pre-excavation grouting, the rock will be prepared for blasting by drilling holes in a pattern and loading the explosives. After blasting, supports will be installed in the fresh excavation. These supports may include rock bolts, wire mesh, shotcrete, and/or steel sets. It is anticipated that the blasted rock will be removed in conjunction with the associated drop shaft excavation so that the connection tunnel construction is not on the construction schedule's critical path.

Depending on the diameter, rock connection tunnels can be lined with cast-in-place concrete or pipe. Available materials include pre-stressed concrete cylinder pipe (PCCP), Hobas pressure pipe, high density polyethylene (HDPE) pipe, ductile iron pipe (DIP), mortar-lined steel pipe, polymer concrete pipe, and reinforced concrete pipe (RCP). Material selection will be based upon connection tunnel characteristics, ground conditions, and diameter and will be further evaluated during the detailed design phase of the project. If pipe is used as the liner, the annular space between the pipe and the initial support and rock will be filled with cellular concrete, concrete, or grout.

7.3.2 Excavation, Support, and Lining of Soft Ground Connection Tunnels

Soft ground tunnels will be located in a productive aquifer that provides water for municipal use. It is expected that the aquifer contains saturated alluvial materials consisting primarily of sand. Groundwater control will be required during tunneling. For the soft ground tunnels, the groundwater inflow can be controlled through conventional TBM methods while dewatering using compressed air or tunneling with a mechanical EPBM and a water-tight liner.

For soft ground tunnel construction, dewatering along the entire alignment is not anticipated to be practical. However, limited dewatering applications may be beneficial for shorter localized connection lengths. This limited dewatering is anticipated only when connecting short soft ground tunnels to longer (primary) soft ground tunnels. Soft ground tunnels could be excavated by pipe-jacking, microtunneling, or using an open-face tunneling methodology within a shield and an excavating bucket or spade.

7. CONSTRUCTION CONSIDERATIONS

Steel Ribs and Wood Lagging Installation

As the tunnel advances, dewatering should continue until a water-tight initial support or final lining is installed. For a single-pass system, water-tight initial support options include jacked pipe, gasketed steel liner plates and gasketed pre-cast segmental concrete. For a two-pass system, the recommended support system includes circumferential steel ribs with wood lagging spanning between the ribs or steel liner plates.

Depending on the diameter, the soft ground connection tunnels can be lined with cast-in-place concrete or pipe. Available materials include pre-stressed concrete cylinder pipe (PCCP), Hobas pressure pipe, high density polyethylene (HDPE) pipe, ductile iron pipe (DIP), mortar-lined steel pipe, polymer concrete pipe, and reinforced concrete pipe (RCP). If pipe is used as the liner, the annular space between the pipe and the initial support will be filled with cellular concrete, concrete, or grout.

Compressed air may be used for the construction of soft ground tunnels beneath the water table. The compressed air method involves constructing the entire tunnel under elevated air pressures to overcome the hydrostatic pressure in the ground. The elevated air pressure prevents groundwater from flowing into the tunnel and prevents ground instability. This elevated air pressure maintains acceptable working conditions in the open excavation. This method is seldom used because of the relatively high cost associated with restricted working hours

7. CONSTRUCTION CONSIDERATIONS

under elevated pressure; lost time for decompressing the workers; and safety-related concerns associated with working under elevated pressures. The compressed air method also includes an elevated fire hazard. The hazard is due to the oxygen-rich environment and blowouts of air into openings in the subsurface that cause the excavation to become unstable or groundwater to flow into the tunnel. It is anticipated that compressed air tunneling will not be considered for this project since mechanical tunneling can be done at a competitive cost and provides a safer working environment.

A mechanical EPBM will be used to drive and construct all soft ground connection tunnels that are below the water table; in areas where dewatering is not feasible; and are of considerable length. A screw conveyor removes the excavated material from the EPBM's pressurized chamber and the muck is conveyed to the surface. It is anticipated that the excavated sand will require conditioning with slurry or polymers in the working chamber to reduce friction and torque in the cutterhead and screw conveyor. Pre-cast concrete segmental liners will be erected in the EPBM's tail shield as it advances. These liners serve as the support and final lining of the tunnel.

Soft Ground EPBM

7. CONSTRUCTION CONSIDERATIONS

7.4 SHAFT CONSTRUCTION

Working, retrieval, intermediate working, Deep Tunnel Pump Station, access, and drop shafts will be constructed for this project. The working, retrieval, intermediate working, Deep Tunnel Pump Station, and any soft ground tunnel working and retrieval shafts will be large in diameter. The access and drop shafts are anticipated to be 14 feet or less in diameter. Shafts associated with the main tunnel, Deep Tunnel Pump Station, drop shafts, and shafts conveying CSOs from soft ground tunnels to the main tunnel will extend into rock. Shafts associated solely with shallow soft ground tunneling will not extend into rock.

7.4.1 Excavation, Support and Lining

The shaft construction methods for this project will depend on the geotechnical and hydrogeologic properties of the soil and rock at each shaft location. It is assumed that the soils consist primarily of saturated sand and are 65 to 120 feet deep along the alignment. Based on available geotechnical information, the sand is underlain by jointed limestone and dolomite units, which constitute a productive bedrock aquifer. Dewatering during shaft construction is considered impractical because of the requirement to draw down the piezometric surface 200 to 300 feet below ground surface. Dewatering may be feasible during soft ground tunneling for shallow shafts if the impact to adjacent water supply wells can be controlled.

During and after excavation, shafts will require support in the soil and at the soil/rock interface. The type of shaft support used will depend on the excavation method; the behavior and stability of the soil; and groundwater control method. Groundwater control should continue until a water-tight support or lining is installed.

7. CONSTRUCTION CONSIDERATIONS

7.4.2 Main Tunnel Working, Retrieval, Intermediate Working, and Deep Tunnel Pump Station Shafts

The main tunnel's working, retrieval, intermediate working, and deep tunnel pump station shafts are anticipated to be 40 to 50 feet in diameter and at a depth of 100 to 200 feet into rock. Groundwater control will be required until a water-tight liner is installed. Construction methods used for large diameter shafts in productive aquifers include:

- Constructing a slurry wall through the overburden and pre-excavation grouting prior to blasting the rock
- Freezing the groundwater in the soil and rock
- Sinking caissons through soil and blasting rock following pre-excavation grouting
- Constructing secant piles through soil and blasting rock following pre-excavation grouting.

The typical slurry wall construction sequence includes:

- Drill and grout the bedrock from the ground surface using tightly spaced grout holes located in two circular rows around the planned shaft's perimeter
- Excavate trenches to the bedrock and hold open using a slurry around the shaft perimeter

Clamshell for Slurry Wall Construction

- Key slurry trenches into the bedrock using a clam shell, chisel, or hydro-fraise depending on the geology
- Lower a rebar cage into the slurry trench to displace concrete
- Excavate the interior concrete walls to the rock
- Blast and remove rock from the hole in intervals until the final depth is reached
- Support rock
- Install reinforced concrete liner/structure the entire depth of the shaft

Slurry Wall Constructed Shaft

The working, retrieval, intermediate working, and Deep Tunnel Pump Station shafts should be lined with reinforced concrete. The working shaft will be converted into the screening shaft and connected to the Deep Tunnel Pump Station shaft by a connection tunnel.

7.4.3 Soft Ground Tunnel Working and Retrieval Shafts

Soft ground tunneling shafts will be approximately 15 to 25 feet in diameter and are anticipated to be constructed only in soil. Commonly, these shafts are braced excavations. Trackhoes and clamshells remove the soil while the formation is dewatered. However, since the main working and retrieval shafts associated with the soft ground tunnels are located adjacent to Fall Creek, White River, or the City's well fields, dewatering may not be advisable or feasible.

7. CONSTRUCTION CONSIDERATIONS

A caisson is a cost effective alternative to construct these shafts. The caisson is designed as the final reinforced concrete lining of the shaft to carry all earth and hydrostatic loads. The typical sequence for sinking a caisson includes:

Braced Shaft Excavation

- Excavate shallow trench around the perimeter of the shaft to identify shallow obstructions
- Pour short circular reinforced concrete lift (shaft wall) in forms set in the trench with the bottom of the wall fitted with a steel cutting shoe
- Excavate soil in the shaft interior and pour an additional reinforced concrete lift varying from about 8 to 20 feet high on top of the existing wall
- Excavate soil in the shaft interior as the shaft wall slides down by gravity
- Add weights to assist the sliding process
- Place bentonite along the outside of the shaft walls to provide lubrication
- Continue the previous steps until the final depth of the shaft is reached

Caisson Construction

7. CONSTRUCTION CONSIDERATIONS

- Allow water to remain inside the wall to equalize the groundwater pressure and prevent the sand from heaving up into the caisson during excavation
- Construct thick concrete bottom plug under water at the base of the excavation that is structurally tied to the shaft walls to prevent the caisson from floating
- Remove water from the caisson interior once the bottom concrete plug has cured

Shaft Excavation while Sinking a Caisson

Drilled secant piles or driven sheet piles with a bottom plug are other alternative construction methods. These methods require that a reinforced concrete liner shaft be placed inside the secant pile or sheet pile perimeter to complete the shaft construction.

7.4.4 Drop Shafts and Access Shafts

It is anticipated that all of the drop and access shafts will be drilled through soil with rock excavated by blasting. Large pier drilling rigs may be utilized to drill holes in the soil up to 14 feet in diameter. It is anticipated that these drops will serve as the working shafts

Drilled Shaft Equipment

for the small connection tunnels. Therefore, the shaft diameter should be larger than the estimated 2 to 7 feet needed for the drop pipe alone to accommodate these activities. Working from each drop shaft to construct the connection tunnels should allow for minimal interferences between multiple contractors and ensure not being on the schedule's critical path.

Steel Casing for Drilled Shaft

Prior to drilling the shaft, tightly spaced pre-excavation grout holes should be drilled and grouted in two circles around the perimeter of the shaft. The shaft should be drilled blind through the overburden using a slurry to keep the borehole open and return the cuttings to the surface. The borehole should be drilled into rock a short distance and cased with steel. Due to the large diameter, the steel casing needs to be welded together at the shaft site and lowered into the hole in sections. Once the section is lowered in the hole, it should be suspended with cables and/or chains while the next section is lifted and welded to it. This process is repeated until the bottom of the hole is reached. The annular space between the ground and casing should be grouted. Once the grout sets, the casing interior should be dewatered so that rock mining can commence. The rock should be drilled and blasted in vertical intervals until the final shaft depth is reached. When excavating in rock, the shaft may require little or no support. If necessary, the rock can be supported with rock bolts and/or shotcrete with or without steel reinforcing. Highly fractured or broken rock zones in the shaft can be lined with steel ribs and lagging or steel liner plates, which can be made water-tight by gaskets.

7. CONSTRUCTION CONSIDERATIONS

Raise bore is a construction method that entails drilling from the connection tunnel up to the ground surface. This construction method will not be feasible because the shaft needs to be constructed prior to the connection tunnel to ensure not being on the schedule's critical path.

The lining of each drop shaft will vary depending on the shaft configuration. If a plunge drop configuration is used, the shaft and deaeration chamber should be lined with reinforced concrete. If a vortex drop configuration is used, each shaft should have a CSO drop pipe with an estimated inside diameter of 2 to 7 feet. The drop pipe could be constructed using Hobas pressure pipe or HDPE. However, the maximum diameter for HDPE is 63 inches. The drop pipe is encased in concrete along the entire length to prevent buckling. Any remaining annular space is filled with flowable or granular fill.

The advantages and disadvantages of the construction methods are presented in Table 7.1. The preferred method for shaft construction is a slurry wall through the overburden and pre-excavation grouting prior to blasting rock.

7. CONSTRUCTION CONSIDERATIONS

Table 7.1
Construction Methods

Construction Method	**Advantages**	**Disadvantages**
Constructing a slurry wall through the overburden and pre-excavation grouting prior to blasting the rock	♦ Effective groundwater control if properly constructed and keyed into bedrock	♦ If not keyed into bedrock, groundwater inflow will occur at the soil/rock interface ♦ Larger area needed for shaft construction
Freezing the groundwater in the soil and rock 	♦ Smaller area needed for shaft construction compared to slurry wall construction ♦ Provides reliable groundwater control at the soil/ rock interface if the hydrogeologic conditions are favorable	♦ Expensive ♦ Can only be applied in appropriate hydrogeologic environments
Sinking caissons through soil and blasting rock following pre-excavation grouting	♦ Smaller area needed for shaft construction compared to slurry wall construction ♦ Could be keyed into shale bedrock to limit groundwater inflows ♦ May be more cost effective than slurry wall construction	♦ Caissons are difficult to key into limestone or dolomitic rock ♦ Leaves a pathway for groundwater and soil infiltration into the excavation

Table 7.1
Construction Methods

Construction Method	**Advantages**	**Disadvantages**
Constructing secant piles through soil and blasting rock following pre-excavation grouting	♦ Smaller area needed for shaft construction compared to slurry wall construction ♦ Potentially more cost effective than slurry wall construction	♦ Secant piles are difficult to drill to these depths without creating windows for groundwater and soil inflows due to deviation of the holes during drilling

7.5 POWER AVAILABILITY

The TBM and associated trailing gear for the main tunnel will require a significant amount of power for operation. The size of the tunnel and geotechnical properties of the rock will dictate the power requirements. All of the working shaft site alternatives should be located in or near industrial areas. Therefore, it is anticipated that power will be available at the site for TBM operation. Drill-and-blast mining and soft ground tunneling machines require less power. Further investigation during design should be performed to evaluate power requirements for the TBM and EPBM.

Sufficient power is likely available for the Deep Tunnel Pump Station and screen facility if the preferred Bluff Road working shaft site is selected. Subsequent design phases should examine the power requirements.

7. CONSTRUCTION CONSIDERATIONS

7.6 HANDLING AND DISPOSAL OF TUNNEL AND SHAFT SPOILS

Spoils (muck) from the main tunnel will be transported from the TBM trailing gear to the working shaft by muck trains pulled by locomotives or conveyor belts. An area should be available onsite to temporarily stockpile the muck. It is anticipated that trucks will be transporting muck from the working shaft site to the disposal site(s) each day the TBM is advancing. Approximately 2,500 cubic yards of material will be generated daily, assuming the tunnel has a 34-foot excavated diameter; advances at an average rate of 50 feet per day; and using a bulking factor of 1.5. This volume will result in approximately 125 trucks per day, with a volume of 20-cubic yards, transporting muck from the working shaft to the disposal site. For traffic impact and cost considerations, adjacent disposal sites should be identified during design. In addition, following the geotechnical investigation, local quarry operators should be contacted to determine their interest in the material. Rock tunnel muck is expected to be suitable for many applications, particularly related to roadway construction.

Special consideration may be necessary to handle and dispose of the spoil generated from the EPBM tunneling. This material, consisting of soil, water, bentonite, and/or polymers and conditioners, may require an offsite location for disposal.

7.7 HANDLING, TREATMENT AND DISCHARGE OF TUNNEL WATER

The contract documents should include provisions for the contractor to handle, treat, and discharge the water generated during shaft and tunnel construction. The provisions should include a package treatment plant at the working shaft site to remove total suspended solids and contaminants prior to discharge. Following treatment, it is anticipated that the water will be discharged to White River. Also, a small package treatment plant may be necessary at the retrieval shaft or drop shafts along the alignment to remove suspended solids and contaminants prior to discharge into White River or Fall Creek. Further characterization of the subsurface is necessary to estimate the volume and quality of water to be treated during construction. A permit will be required to discharge the treated water to White River or Fall Creek.

7.8 PROTECTION OF EXISTING STRUCTURES

Protecting existing structures from damage will be addressed during design and construction. A pre-condition survey should be required of the contractor prior to executing shaft or tunnel construction. Instrumentation will be required to monitor settlement, ground movement, and impacts to groundwater. Inclinometers and vibration monitoring instruments (seismographs) will be located on structures; on utilities; at the ground surface; and at observation wells. Periodic readings before, during, and after construction will allow for a quick response if the monitoring limits are exceeded. These responses can include:

- Ceasing the operation and developing a corrective action plan
- Providing additional protection measures to the structures
- Requiring a change in the contractor's methodology

The effects on existing structures during construction may be minimized since the tunnel will be mined in deep rock. Settlement is not anticipated to be an issue, excluding an encounter with a major filled joint connected to the overburden flowing into the tunnel face. Minimal vibrations may be noticed at the surface within a couple hundred feet of the operating TBM. However, the vibrations will occur over a short duration and are not anticipated to be of a magnitude that causes structural damage. To the extent possible, the main tunnel alignments were routed away from vibration sensitive structures, such as hospitals.

Tunneling in soil typically increases the risk of damaging nearby structures or property. While some of these risks associated with ground loss and settlement can be mitigated using a mechanical EPBM, the potential to damage existing structures is present. This includes causing surface settlement and encountering an unknown utility and disrupting service. Surface settlement caused by ground loss at the tunnel heading can occur when the tunnel envelope is over-excavated. This happens when an obstruction straddling the tunnel envelope is removed in its entirety at the cutting face and creates a void behind the tunnel shield. Sand has a tendency to collapse in this void prior to the lining installation. Settlement can occur if the void caused by the collapsing sand travels up to the surface. In addition, if not controlled, the circulation fluid that pressurizes the face can be lost to an opening in the subsurface. This will cause the observed pressure at the tunnel face to be higher than at the cutterhead chamber. Water and soil may flow into the tunnel and potentially result in surface settlement. While these risks exist, they can be mitigated with proper design using data obtained from a geotechnical program and sound construction practices.

Ground loss also can occur during shaft construction causing settlement and potentially damaging nearby structures. Proper design and construction practices along with a sufficient monitoring program can assist to mitigate these risks.